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EFFECTS OF SIMULATED SPACE ENVIRONMENT ON FULL-, HALF-, AND QUARTER-SIZE CADMIUM SULFIDE THIN-FILM SOLAR CELLS

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16. Abstract

Full-, half-, and quarter-size CdS thin-film solar cells were subjected to a simulated space environment to test the effect of cell size on performance degradation. The test data indicate that there is more variation in degradation among common size cells than between different size cells and that cell degradation does not appear to be substantially affected by cell size.

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EFFECTS OF SIMULATED SPACE ENVIRONMENT ON FULL-, HALF-, AND QUARTER-SIZE CADMIUM SULFIDE THIN-FILM SOLAR CELLS

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SUMMARY

The electrical performance of cadmium sulfide (CdS) thin-film solar cells degrades under conditions of simulated Earth orbit environment. Tests showed that cells will delaminate under severe thermal shock. Cross-sectional photomicrographs of CdS cells showed lamellar cracks. There was reason to believe that, under the less severe thermal shock of simulated low-Earth-orbit testing, small thermal stresses were causing cracks within the cell which were contributing to cell degradation. Additionally, there was speculation that cell size, by affecting the thermal stress-induced cracking, was a factor in cell degradation.

Answers to these questions were sought by vacuum thermal cycling full-size (3- by 3-in. (7.62- by 7.62-cm)), half-size (3- by 1.5-in. (7.62- by 3.81-cm)), and quarter-size (3- by 0.75-in. (7.62- by 1.91-cm)) cells and comparing degradations. In the limited test sample, there is more variability in the degradation among half- and quarter-size cells cut from the same full-size cell than among cells of different sizes. The conclusion is that factors other than cell size have a predominate effect on cell degradation.

INTRODUCTION

Solar cells in Earth orbit range in temperature from 65° C (338 K) in sunlight to -195° C (78 K) in the dark. The electrical performance of the CdS thin-film solar cell being developed by the Clevite Corporation under contract to the Lewis Research Center degrades under this type of simulated space environment (refs. 1 and 2). This CdS cell is composed of six layers of materials each having a different coefficient of thermal expansion. The magnitude of the thermal stresses generated within the cell during the temperature variations of simulated space tests was not known. Repeatedly dipping cells in liquid nitrogen and then heating them to 60° C (333 K) had shown, however, that full-size cells delaminate under severe thermal shock (ref. 3). It seemed possible, therefore, that the less severe simulated space tests were causing less severe but related damage which was in turn degrading cell performance.

Simple theory predicts that the magnitude of these thermal stresses depends on the size of the cell. Smaller cells should have lower stresses than larger cells and should degrade less if cell damage resulting from thermal stresses were causing degradation.

The effect of cell size on cell degradation was investigated by placing, full-size (3- by 3-in. (7.62- by 7.62-cm)), half-size (3- by 1.5-in. (7.62- by 3.81-cm)), and quarter-size (3- by 0.75-in. (7.62- by 1.91-cm)) cells cut from the same full-size cell in a vacuum chamber and thermal cycling them with a solar simulator through 350 cycles. Each cycle consisted of an illuminated period of 1 hour, during which cell temperature rose to 65° C (338 K), and a dark period of 1/2 hour, during which the cell temperature dropped to -150° C (123 K). Cell performance characteristics were measured under controlled conditions in air prior to and immediately following vacuum thermal cycling. These data were used to determine cell degradations and to compare the performance of the three different size cells.

SYMBOLS

AMO	air mass zero sunlight at 1 astronomical unit
FF	fill factor, $P_{max}/V_{oc}I_{sc}$
I_{sc}	short-circuit current
P_{max}	maximum power
V-I	voltage-current characteristic of solar cell
V_{oc}	open-circuit voltage

TEST EQUIPMENT AND PROCEDURES

The ambient test equipment was used to obtain CdS cell voltage-current (V-I) characteristics prior to and following cutting, and temperature coefficients prior to and following vacuum thermal cycling testing. The equipment consists of a temperature controlled block with provisions for cell vacuum holddown and temperature variation, a tungsten-iodine light source filtered through 1 gram per liter copper sulfate solution,

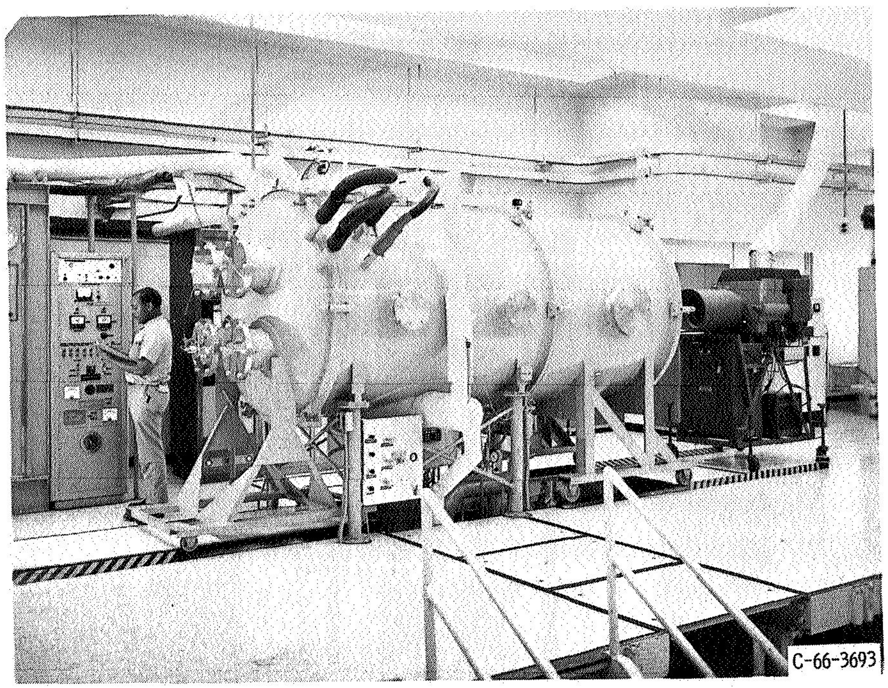


Figure 1. - Vacuum chamber and carbon arc solar simulator.

and an electronic load. The light intensity is set using a standard CdS cell calibrated in an airplane (ref. 4).

The electronic load is a solid-state instrument which automatically varies the load on a solar cell so that the V-I characteristic may be traced on an X-Y recorder.

A 5- by 12-foot (1.52- by 3.66-m) vacuum chamber (fig. 1) having liquid-nitrogen-cooled walls capable of maintaining a measured vacuum of 1×10^{-8} torr (ref. 5) was used for vacuum thermal cycling tests. The liquid-nitrogen walls maintain solar cell temperatures at about 65° C (338 K) when illuminated with AMO (air mass zero) simulated sunlight. With the solar simulator turned off, solar cell temperature drops to -150° C (123 K) in about 3 minutes.

A Strong Electronic Co. high-intensity carbon arc lamp capable of running unattended for 24 hours was used as the solar simulator (ref. 5).

The light intensity was monitored with four silicon solar cells mounted in the test plane (fig. 2(a)) and connected to a four-channel strip-chart recorder.

Cell temperatures were recorded by a 24-point temperature recorder and a copper-constantan thermocouple attached to the center of each cell. The welded 40-gage wires were attached to the back of each cell with a 1-square-centimeter piece of Schjeldahl T320 Kapton tape. A small amount of thermal conducting compound was applied between the thermocouple and the cell.

The illumination uniformity in the test plane of the 5- by 12-foot (1.52- by 3.66-m) vacuum chamber was checked prior to this test. The intensity at the center of the test

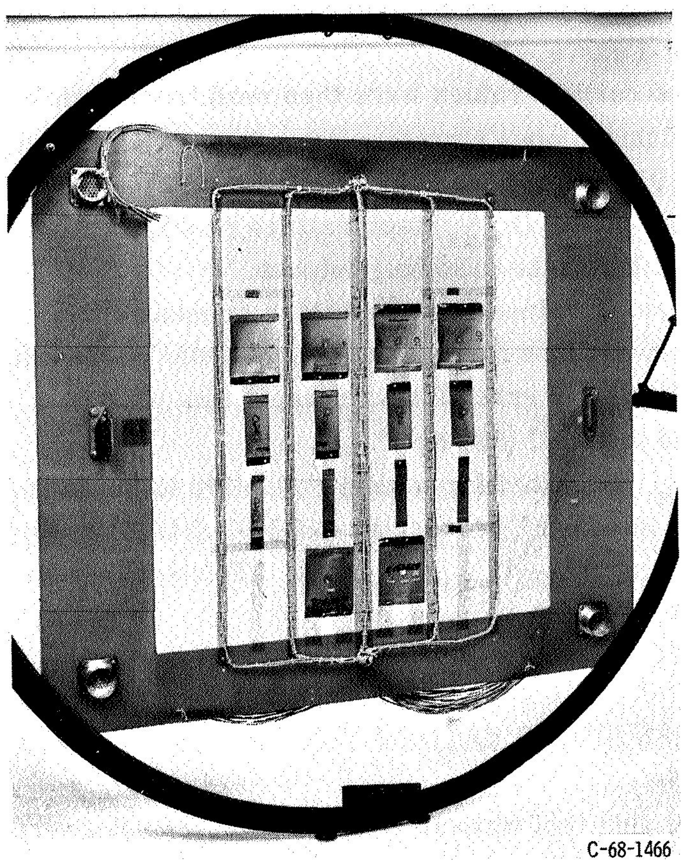
(a) Front view.

Figure 2. - Cadmium sulfide solar cells mounted on vacuum thermal cycling mounting fixture.

plane was set at 1.1 AMO suns using an Eppley thermopile. Previous illumination uniformity data showed the intensity to vary approximately ±5 percent over the test plane. The 1.1 sun intensity level was selected, therefore, so that no point in the test plane would be below AMO intensity.

The intensity in the test plane was mapped by using two silicon solar cells: one mounted stationary near the bottom of the test plane and the other mounted on a moving arm. Continuous vertical readings were taken at 4-inch (10.16-cm) horizontal intervals. The results of this mapping confirmed previous mappings in that the intensity varied approximately ±5 percent from a mean setting.

The cell mounting assembly used in the vacuum chamber is shown in figure 2. The 1/8-inch- (0.32-cm-) thick glass epoxy mounting frame is attached to an aluminum ring which rolls on cantilevered arms extending from the rear bulkhead of the vacuum chamber. The cells are attached to each other and to the mounting frame by pieces of 1-mil- (25.4-μm-) thick Schjeldahl T320 Kapton tape. This design allows only minimum thermal conduction to and from the cells.



(b) Rear view.
Figure 2. - Concluded.

Two pieces of No. 22 single strand wire were soldered to each lead tab of each cell. One wire was used to measure cell voltage; the other wire was the current, or load, conductor. The four silicon cells used to monitor light intensity were mounted by using the T320 Kapton tape, but had only one current carrying wire to each cell contact.

The two silicon cells mounted on the right side of the mounting frame (fig. 2(a)) were used to trigger an elapsed-time clock that measured the amount of time the CdS cells were illuminated.

The CdS cells were loaded at the maximum power point determined from the 65° C (338 K) V-I curves taken on the ambient test equipment.

DATA ACQUISITION AND REDUCTION

Cell performance during simulated space environment testing was calculated from V-I curves taken with an electronic load and an X-Y plotter. Cell temperature and light intensity were recorded while the V-I curve was being taken. The operating voltage of each cell, that is, the cell voltage when connected to the fixed load, was recorded just prior to taking each V-I curve.

Eleven voltage and current values were then read from each V-I curve at fixed voltages. These points included open circuit voltage (V_{oc}), short circuit current (I_{sc}), and a current value at -0.05 volt. These data along with cell temperature, light intensity, and V_{oc} and maximum power (P_{max}) temperature coefficients were the inputs for a computer program that listed the following outputs:

(1) Voltage and current values for a computer-generated V-I curve (a curve fit using the least-squares method and fourth-order polynomial equation) and its deviation and relative error from the input data points

(2) V_{oc} corrected to 60° C (333 K)

(3) I_{sc} and P_{max} corrected for intensity relative to the intensity reading at cycle 1

(4) P_{max} and fill factor (FF) corrected to 60° C (333 K) and intensity at cycle 1

(5) Relative values of V_{oc}, I_{sc}, P_{max}, and FF (compared with those at cycle 1 and corrected for intensity and temperature)

AMBIENT AND VACUUM THERMAL CYCLING TESTS

The cells used for this test were from a group of cells delivered by the Clevite Corporation in September 1967. Eight cells were selected which had very nearly identical V-I curves. Four of these cells were used as full-size cells. The other four cells were cut in half; then one half of each cell was cut in half. Each of these last four cells, therefore, yielded one half-size cell and two quarter-size cells. The cells were cut from the back side using a straight edge and a razor blade.

A V-I curve was taken of each of these full-size cells before being cut into one half-size and two quarter-size cells. Following cutting, V-I curves were taken of each fractional size cell. Comparing the V-I curves of the cell parts from a common cell with the V-I curve of the full-size cell before cutting showed that the cells did not suffer any losses as a result of cutting.

Temperature coefficients of V_{oc} and P_{max} were determined for all cells prior to vacuum thermal cycling. These coefficients were used to correct all data to a common temperature of 60° C (333 K). The cells were then placed in the vacuum chamber and vacuum thermal cycling tests started. The cells were cycled through 350 cycles of $1\frac{1}{2}$ hours each: 1 hour light and 1/2 hour dark. Cell data, in the form of V-I curves, were recorded every 5 cycles for the first 20 cycles and once a day thereafter. Following vacuum thermal cycling, the cells were removed from the chamber, and a V-I curve at 25° C (298 K) was immediately taken on the ambient test equipment. Following this test, the temperature coefficients were measured again.

Maximum power measurements made with the ambient test equipment have a standard deviation of ±1.18 percent. This was established by an analysis-of-variances study performed at the Lewis Research Center and at three other cooperating laboratories (ref. 2). The measurement procedures used for this cell-size experiment duplicated those used for the study.

RESULTS AND DISCUSSION

The data for the first 20 cycles of vacuum thermal cycling showed an anomalous increase in short-circuit current and consequently in maximum power. Cell behavior following this initial increase in performance was normal when measured relative to the highest maximum power readings. It was, however, impossible to determine accurately and with assurance the actual amount of degradation in cell performance from data taken during vacuum thermal cycling. These data (shown in the appendix) were therefore set aside in favor of the before and after ambient test data. It should be noted, however, that others (refs. 6 and 7) report similar increases in short-circuit current.

TABLE I. - ABSOLUTE VALUES[a] OF CELL PERFORMANCE CHARACTERISTICS BEFORE AND AFTER VACUUM THERMAL CYCLING

Cell size	Cell number	Short-circuit current, I_{sc}, A		Maximum power, P_{max}, W		Fill factor, FF	
		Before	After	Before	After	Before	After
Full	1	0.769	0.730	0.196	0.193	0.615	0.622
	2	.734	.679	.198	.178	.603	.633
	3	.789	.754	.210	.195	.608	.630
	4	.756	.694	.188	.162	.540	.590
Half	5	0.385	0.354	0.095	0.080	0.518	0.570
	6	.389	.362	.102	.089	.570	.612
	7	.392	.372	.106	.097	.632	.652
	8	.367	.335	.104	.090	.615	.652
Quarter	5	0.196	0.182	0.049	0.042	0.538	0.588
	6	.200	.188	.050	.045	.560	.594
	7	.195	.183	.054	.050	.638	.652
	8	.186	.169	.053	.047	.638	.665

[a]All values taken in air at 60° C (333 K) under simulated AMO sunlight. Precision: I_{sc}, ±0.01 I_{sc}; FF, ±0.04 FF; and P_{max}, ±0.0118 P_{max}.

The average maximum power losses determined from data taken on the ambient test equipment before and after vacuum thermal cycling are 8.3 percent for full-size cells, 12.4 percent for half-size cells, and 10.7 percent for quarter-size cells. The individual cell data are shown in tables I and II. Table II is arranged to show the data from each cell in the same position that cell occupied during vacuum thermal cycling (see fig. 2(a)).

The performance of cell number 1 is considerably different from any other full-size cell. This difference is most likely the result of the great number of V-I curves taken of this cell while trying to find the cause of the current increases. Tests have since shown that taking a V-I curve of a degrading cell may cause the cell to regain some of

TABLE II. - EFFECT OF VACUUM THERMAL CYCLING ON MAXIMUM POWER, FILL FACTOR, AND SHORT-CIRCUIT CURRENT

[Data shown are arranged by cell position in vacuum chamber shown in fig. 1. Measurements were made in air at 60° C (333 K) under simulated AMO sunlight. Values represent difference in performance from before to after vacuum thermal cycling test.]

	Full-size cells			
Cell number	1	2	3	4
Percent change in maximum power (P_{max})	-1.4	-10.4	-7.1	-14.2
Percent change in fill factor (FF)	1.1	4.7	3.6	8.5
Percent change in short-circuit current (I_{sc})	-5.0	-10.2	-4.4	-8.2

	Half-size cells			
Cell number	5	6	7	8
Percent change in maximum power, (P_{max})	-15.8	-12.6	-8.4	-12.9
Percent change in fill factor (FF)	9.1	6.9	3.0	5.8
Percent change in short-circuit current (I_{sc})	-8.0	-6.8	-5.2	-8.7

	Quarter-size cells			
Cell number	5	6	7	8
Percent change in maximum power (P_{max})	-13.9	-9.9	-7.5	-11.4
Percent change in fill factor, (FF)	8.5	5.6	2.1	4.1
Percent change in short-circuit current (I_{sc})	-7.2	-6.0	-6.2	-9.2

Special cells	
(a)	(a)

[a]Associated with thermal shock test not reported herein.

its lost performance (unpublished data obtained by M. P. Godlewski, L. R. Scudder, and T. M. Klucher of the Lewis Research Center).

With the exception of cell number 1, which had a maximum power loss of only 1.4 percent, the cells of each size group behaved very similarly. The range of maximum power loss was from 7 to 15 percent for each group. If cell number 1 is eliminated from consideration in the full-size group, the average for that group is 10.6 percent.

Cell degradation between groups was tested using a t-distribution to determine if the difference between the averages for the full-size and half-size groups was statistically significant. The t-value for the difference in the maximum power degradation averages between full-size and half-size cells is 0.714. The average difference in maximum power degradation between full-size and half-size cells at the 95-percent confidence level is 1.8 ± 6.48 percent. Further, since the quarter-size-cell group has an average degradation which lies between those of the other two groups, comparing the quarter-size group with the full-size group also indicates no significant degradation difference.

Comparing half- and quarter-size-cell groups by a paired t-test, however, indicates that cell size may influence degradation to some extent. As shown in table II, half- and quarter-size cells cut from the same full-size cell show similar degradations; each half-size cell shows slightly greater degradation than its quarter-cell mate. The average difference in power loss between paired cells was 1.7 percent. The paired t-value for this difference in averages is 4.25. The average difference in maximum power degradation between half- and quarter-size cells at the 95-percent confidence level is 1.75 ± 1.27 percent.

Cell size, however, does not appear to be the most important factor influencing cell degradation. As shown in table II, some quarter-size cells showed greater degradation than some half-size cells. Furthermore, the variance within a given cell-size group is much greater than the variance of the difference between half- and quarter-size cells. Thus, there is more variation among common size cells then between cell size groups. The final conclusion is that factors other than cell size have a predominate effect on cell degradation.

SUMMARY OF RESULTS

Full-size, half-size, and quarter-size cadmium sulfide thin-film solar cells were subjected to simulated space environment testing to determine if cell degradation were a function of cell size. Results show that

1. Average maximum power degradation was 10.6 percent for full-size cells, 12.4 percent for half-size cells, and 10.7 percent for quarter-size cells. These results

are based on measurements of cell performance taken before and after 350 vacuum thermal cycles. Performance measurements were made in air at 60° C (333 K) under simulated air mass zero sunlight.

2. Comparing the full-size-cell group with either the half- or quarter-size-cell groups shows no significant difference in maximum power degradation between groups. Half- and quarter-size cell pairs cut from the same full-size cell do show small differences in degradation however.

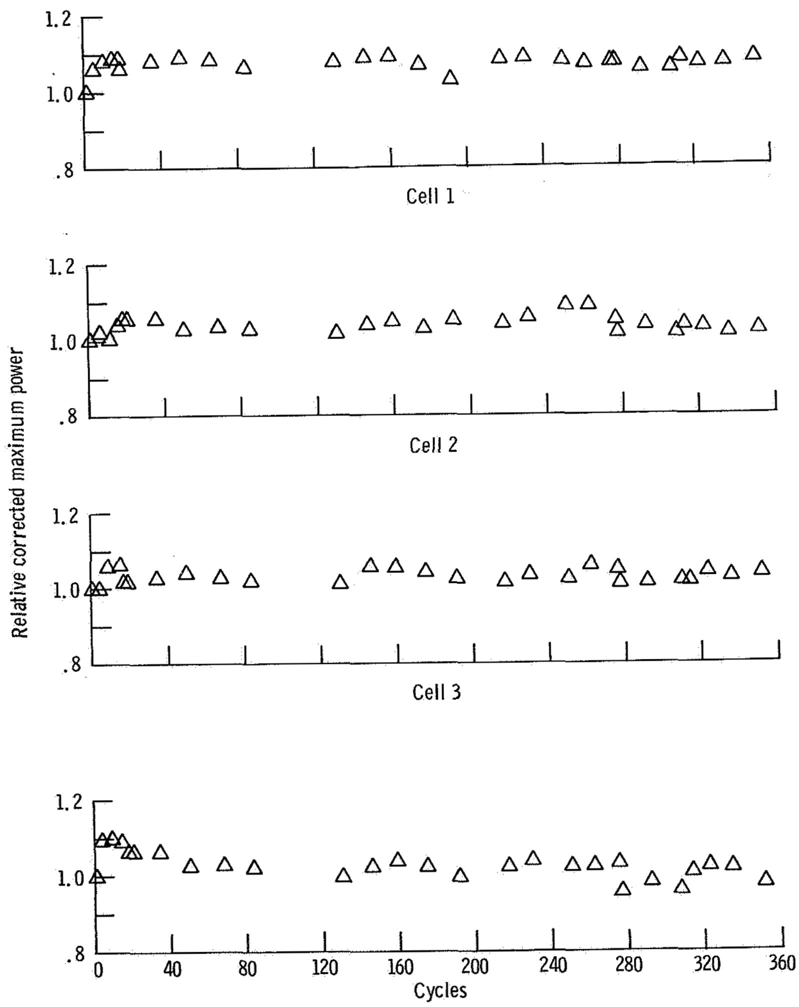
3. There is more variation in degradation among common size cells than between different size cells cut from the same full-size cell.

4. Cell degradation does not appear to be substantially affected by cell size.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, July 15, 1969,
120-33.

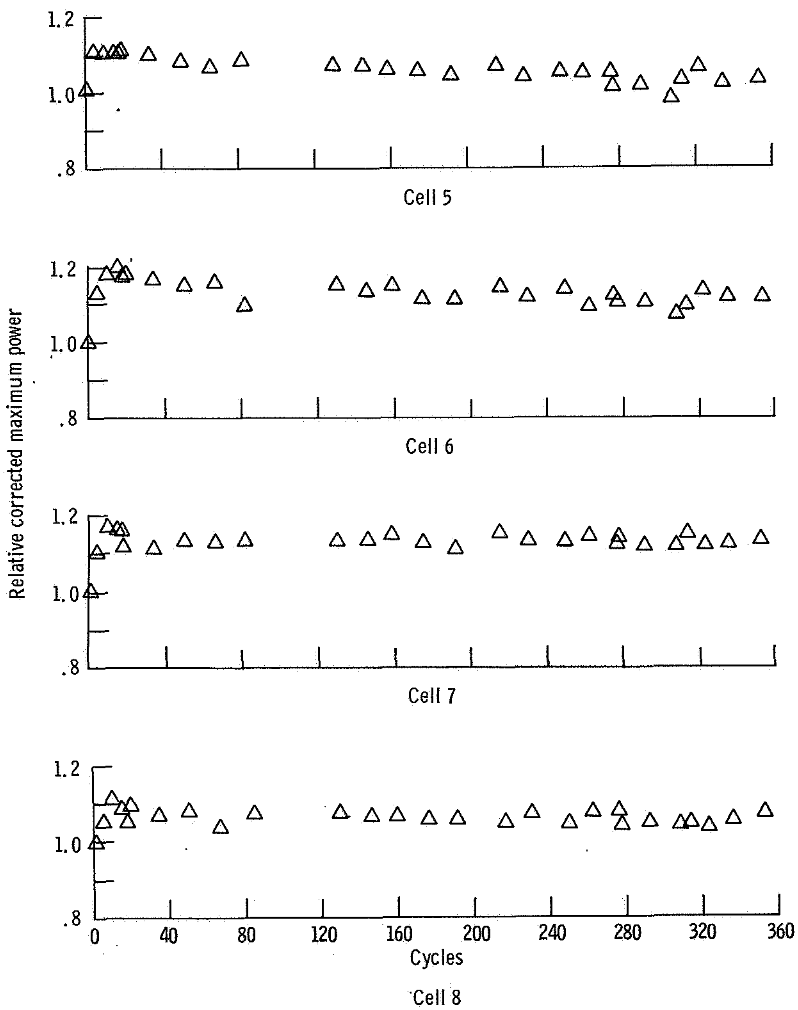
APPENDIX - VACUUM THERMAL CYCLING DATA

Data taken during vacuum thermal cycling show the increase in maximum power (fig. 3) resulting from the increase in short-circuit current and are included to allow comparison with similar data seen by others (refs. 6 and 7). The average maximum increase in short-circuit current from cycle 1 was 8.6 percent for full-size cells and 16 percent for half- and quarter-size cells. The average maximum increase in maximum power was 8 percent for full-size cells, 17 percent for half-size cells, and 39 percent for quarter-size cells. A thorough examination of the experimental equipment and procedures has failed to explain these data. Either the experimental procedures are in some way affecting cell performance or these increases are evidence of changes within the cell.



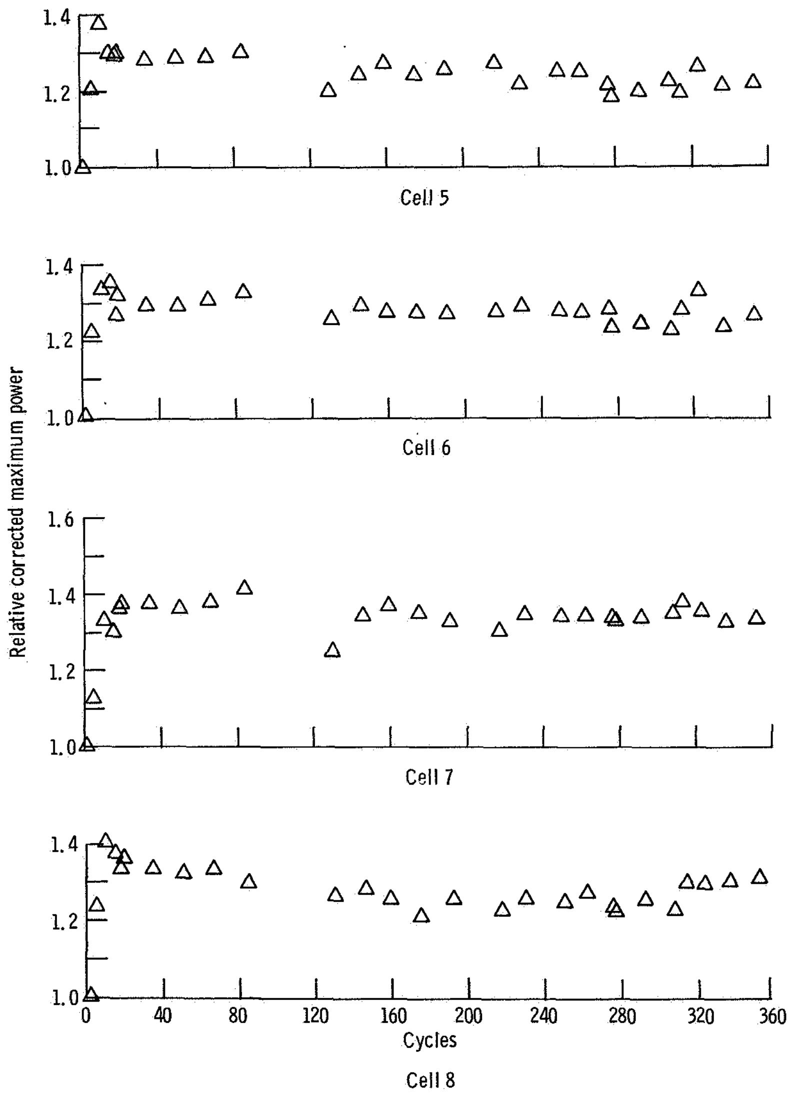
(a) Full-size cells.

Figure 3. - Changes in maximum power during vacuum thermal cycling.



(b) Half-size cells.

Figure 3. - Continued.



(c) Quarter-size cells.

Figure 3. - Concluded.

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